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LUNETTES AS INDICES OF HYDROLOGIC CHANGE: A REVIEW OF AUSTRALIAN EVIDENCE

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Abstract: A variety of transverse dune types occurs on the eastern margins of lake basins across southern Australia. Known collectively as 'lunettes', these range in composition through quartz-rich, sandy clay, gypseous clay to nearly pure gypsum. The origin of the pure quartz dunes formed under lake-full conditions, is distinct from that of the clay or gypsum-rich variety which formed by deflation from adjacent lake floors.

In the lunette forming processes the role of salts and groundwater is critical. Descriptions of modern examples from Texas provide analogues of clay dune building that affected hundreds of small basins across southern Australia during late Pleistocene time at the height of the last glacial episode.

Modern clay deflation examples from Lake Eyre and Lake Tyrrell confirm the role of salts especially halite and, on the edge of Lake Tyrrell, thenardite, in providing the active efflorescent mechanism which physically breaks the near surface gypseous clays into a soft fluffy pelletal layer preparatory for deflation.

The deflationary process, associated with strong frontal systems, raises large dust clouds today from some playa floors involving both suspension and traction loads. Such conditions, favoured by long droughts and strong winds, were intensified during late Pleistocene time when the final and most dramatic phase of regional clay dune (lunette) building occurred across southwestern to southeastern Australia. In this way, the variety of ancient lunette forms, when set beside modern examples both here and overseas, provide a most instructive window to help interpret the legacy of ice age hydrologic and climatic processes that affected large inland regions of the Australian continent.

In 1939 E. S. Hills produced a major paper in these Proceedings dealing with the physiography of north-western Victoria. That paper was noteworthy for two reasons. It assembled for the first time a huge amount of topographic detail drawing upon records from railway and State Rivers channel surveys; in doing so, it produced the first topographic map of the region, highlighting the north-south ridges and other features. Secondly, it provided the first geomorphic analysis of a region which, perhaps above all others in Australia, possesses a diverse and distinctive array of peculiarly Australian landforms, legacies of complex Quaternary environmental changes which were as challenging to Hills in 1939 as they are productive to Quaternary scientists today.

In recording the succession of buried soils within longitudinal dunes near Ouyen, Hills related their origins to past climatic oscillations (soils during humid periods, dune growth in arid phases). Thus he anticipated those cyclic climatic oscillations which later work is only now beginning to clarify. Additionally, in drawing particular attention to the presence of clay-rich transverse dunes on lake margins, he singled out the enigmatic landforms which he went on to name '*lunettes*' (Hills 1940).

Subsequent work involving stratigraphic, chronologic and archaeological studies of lunettes through southeastern Australia has shown them to be rich repositories of the ancient history of climate, animals and Man. In this essay I wish to explore some of the many facets of lake-lunette studies which have burgeoned since the pioneering work of Hills in 1939.

Previous work

On 24 July 1836, Major T. L. Mitchell, on his famous journey through the river systems of south-eastern Australia, noted in his diary:

> I proceeded to examine and survey some of these remarkable lakes. On the margin of one of them . . . a green hill of rather singular shape rose to a considerable height, above the surrounding country. I found the water in the lake beside it, shallow and quite salty . . . This was surrounded by a narrow beach of soft white mud or clay . . . The green hill was the highest of several semi-circular ridges, forms that may perhaps be better understood by the accompanying plan. There was a remarkable analogy in the form and position of all these hills; the form being usually that of a curve, concentric with the lake, and the position invariably on the eastern or north-eastern shores, a peculiarity I had previously observed, not only in the lakes near the banks of the Murray, but also in others of the Murrumbidgee and Lachlan, where the ridge consisted of red sand . . . (Mitchell 1839, pp. 190-191).

Mitchell's description and map (Fig. 2), which were remarkable for their clarity and attention to detail, provide us with the first record of these unusual lake-shore dunes. But for almost the next 100 years, these landforms escaped the attention of Australian geomorphologists.

As so often happens in science, the first systematic observations were made almost simultaneously by two people; Harris (1939) a school teacher at Echuca described loam ridges on the shores of Lake Cooper complex while Hills (1939, 1940) drawing on examples from the Mallee and Kerang set out the systematic description.

From the succession of loam ridges on the shores of L. Benjeroop, Hills (1939) noted that each successive

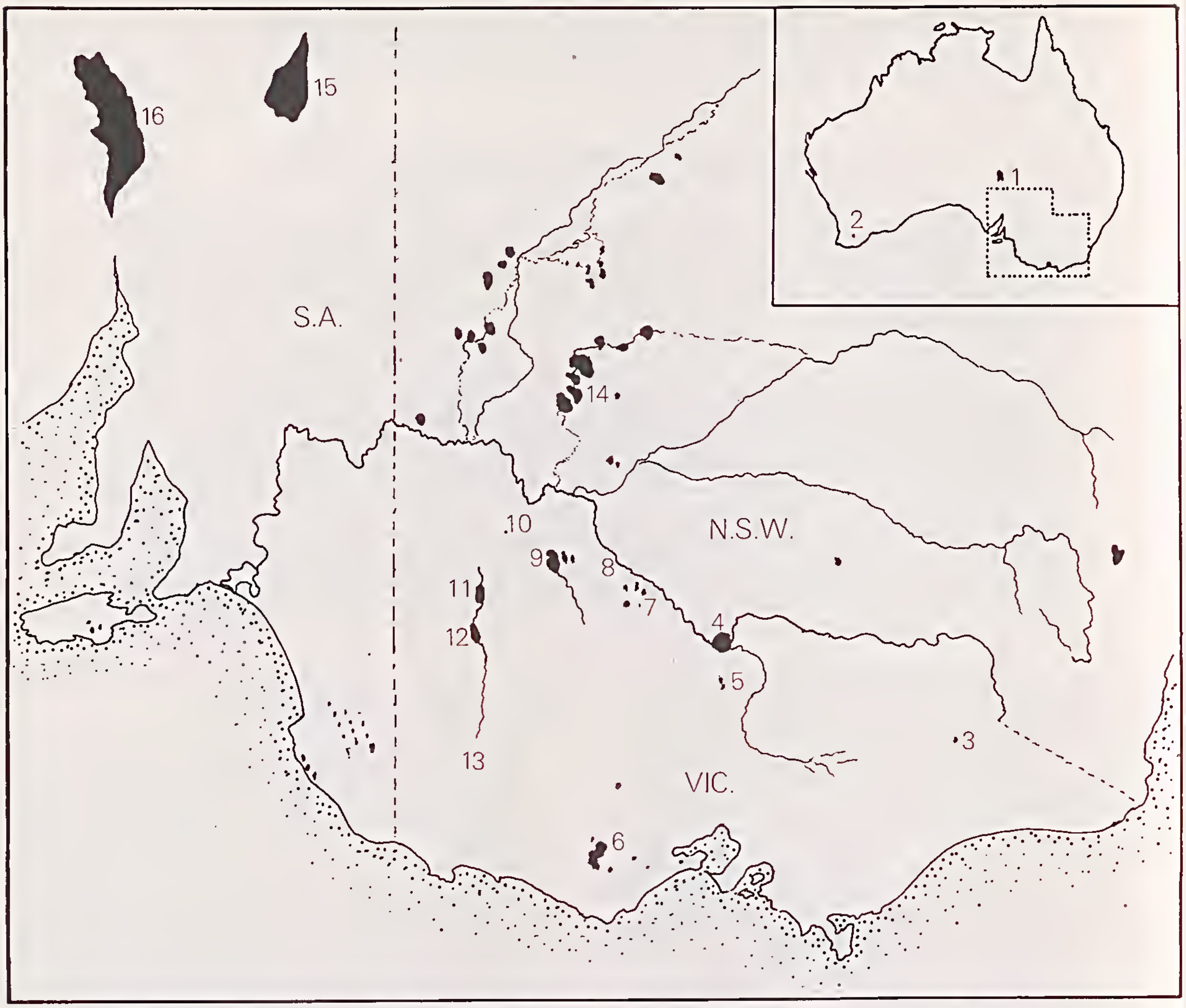

Fig. 1—Location map of sites mentioned in text. 1, Lake Eyre; 2, Wagin Lake; 3, Lake Omeo; 4, Barmah, Echuca, Lake Kanyapella; 5, Lake Cooper; 6, Lake Corangamite; 7, Kerang, Lake Wandella, Benjeroop; 8, Swan Hill; 9, Lake Tyrrell; 10, Ouyen; 11, Lake Albacutya; 12, Lake Hindmarsh; 13, Mitre Lake, Mt. Arapiles; 14, Willandra Lakes—Lake Garnpung, Lake Mungo and Wall of China, Lake Outer Arumpo, Chibnalwood Lakes; 15, Lake Frome; 16, Lake Torrens.

phase was built inside the perimeter of the last; all were on the margin of successively lower lake levels. Thus he established an important relationship between clay dune occurrence and water-level, a relationship which is relevant to many aspects of dune origin. The difficulty of obtaining saltation grains from the lake floor together with the apparent water-level control, led Hills to postulate a mechanism of downwind flocculation of fines by salt spray to produce a local concentration of clay-sized sediment. But he also acknowledged the probable importance of other processes, particularly that of pelletal concentration by deflation from lake floors as demonstrated in Texas (Coffey, 1909). But at that time data from the Texan examples was insufficient to permit detailed comparison to be drawn with the Australian fossil examples (Hills 1940, p. 5).

In the same year that saw the publication of Harris' and Hills' observations, Baldwin, Burvill and Freedman (1939) published the first soil survey in the Kerang district showing the local distribution of clay dunes and their associated soils. They noted that soils on the 'red sand hills' (soil type 4) were of lighter texture and contained significantly more sand than the surrounding heavy clay plains. The profiles had 'reached an advanced stage of maturity' indicating stability for considerable periods, evidence for the relict nature of these forms.

Stephens and Crocker (1946) presented the first regional account of lunettes throughout southern Australia. They described occurrences from Tasmania, Western Australia, South Australia, Victoria and southern New South Wales and provided detailed analyses of the range of textures in vertical profiles

Fig. 2—The first map of lunettes ever made. Greenhill Lake near the Grampian Ranges, western Victoria, surveyed by Major T. L. Mitchell in 1836. Map from Mitchell, 1839.

through representative dunes at various sites. They drew attention to the significance of the wide range in textural composition from coarse sands at Wagin Lake, Western Australia, to the dunes composed mainly of clay as at Kerang, Victoria. They noted some of the difficulties in the spray precipitation hypothesis especially in its failure to account for the coarse sand components. They revived the lake floor deflation theory proposed initially by Harris (1939) pointing out that it provided a satisfactory hypothesis for the textural variation within the sediments, a view supported later by Bettenay (1962). The lunette 'composition is governed by the nature of the material present on the surface of the dry lake floor, and immediately to the windward . . .' (Stephens & Crocker 1946, p. 309). They saw no cause to associate lunette building with the presence of water as claimed by Hills from the multiple lunettes at L. Benjeroop. All lunettes were therefore interpreted as evidence of aridity. In supporting the dry lake deflation hypothesis, Stephens and Crocker did not attempt to explain why similar features rarely form today.

Sprigg (1979), recording lunettes on the continental shelf, emphasised their relict character and age of formation associated with glacial low sea-levels.

For many years the problem of lunette formation and their environmental significance received scant at-

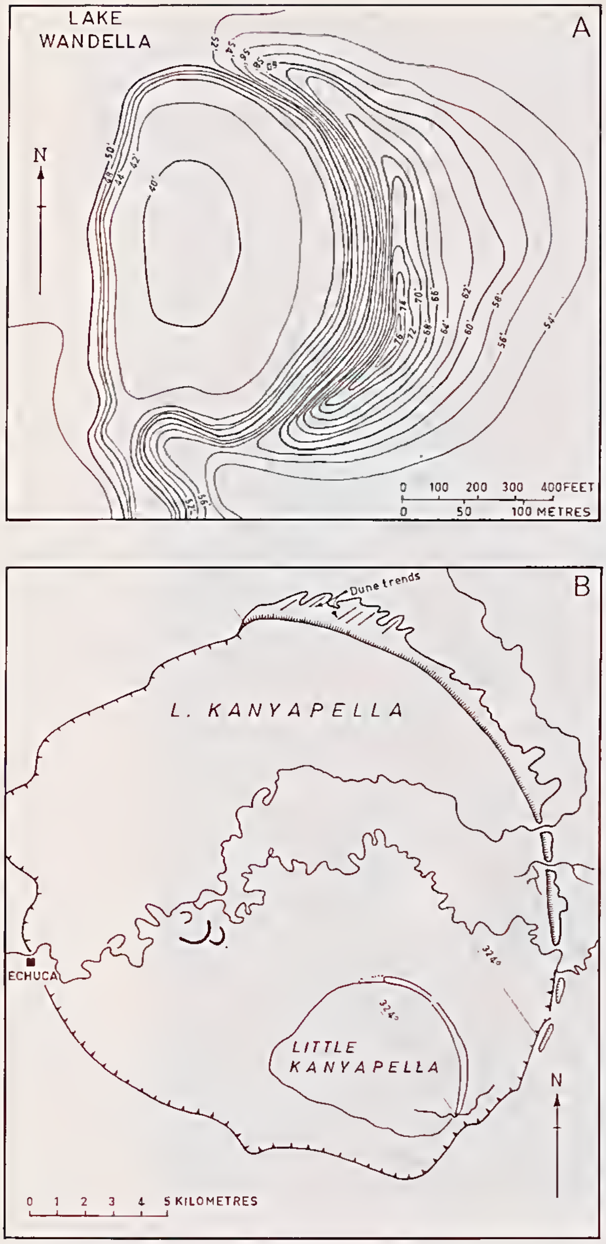

Fig. 3—Typical lunette forms in northern Victoria.
A, clay lunette at Wandella, near Kerang.
B, quartz sand lunette at Kanyapella near Echuca.

tention. Bowler and Harford (1966) in describing the lunette-lake system in the fault-angle depression near Echuca (L. Kanyapella), postulated a high water level origin for the coarse textured sand lunette in opposition to the dry lake theory. Currey (1964) had previously reported the modern deflation of wave transported *Coxiella* shells into a dune on the eastern shores of L. Corangamite, western Victoria, contributing to lunette formation. Thus lunette development is considerably more complex than in the relatively simple dry lake theory advanced by Stephens and Crocker.

In a short account of Australian lunettes Bowler (1968) stated that two distinct types of lunettes exist, the formation of which must be considered separately. Firstly, the quartz sand lunettes with low clay content similar to that at Echuca have developed by deflation from active lakeshore beaches. A similar explanation may also apply to the coarse textured Wagin Lake lunette, Western Australia (Stephens & Crocker 1946, p. 306) and to that with bedded '*Coxiella* shells and quartz grit' shown in section by Bettenay (1962, plate 1). Secondly, those with high percentages of clay were ascribed to deflation from partially exposed lake floors during periods of low water level in a manner similar to that described from Texas (Huffman & Price 1949, Price 1963). Campbell (1968) correctly emphasised the importance of water but went on to relate *all* lunettes to sediment transport by waves preparatory to deflation. She suggested (p. 107) that clays as well as sands might be related to derivation from beaches, an observation which is at variance with observed modern clay deflation.

An earlier review (Bowler 1973) summarised the main sedimentary characteristics of clay-rich lunettes. I propose to discuss here the evidence now available relating to the conditions under which they form, and their hydrologic and climatic implications in the broad context of Quaternary changes in Australia.

QUARTZ AND CLAY DUNE COMPARISON

Throughout southeastern Australia examples of quartz and clay-loam ridges occur often within the same region and sometimes even on the margins of the same basin. We may contrast the regular topographic expression of the clay-rich forms exemplified by Lake Wandella (Fig. 3A) with the irregular hummocky topography, particularly on the downwind margins of quartz dunes as at Lake Kanyapella near Echuca (Fig. 3B; Bowler & Harford 1966). The sedimentary contrast reflected in the different topographic expression is itself reflecting different origins.

The presence of coarse, well-bedded beach sands with low angle lake-ward dips exposed in sand quarries on the road between Echuca and Barmah provides positive evidence of dune construction from relatively high energy beaches during lake-full conditions (Bowler 1980, fig. 3.13). A textural gradient from coarse to fine away from the beach towards the basin centre demonstrates that the dune sands could not have originated by deflation from exposed lake floor. Instead, they formed from beaches in the same way that foreshore dunes form in many coastal situations today (Fig. 4A).

In several important ways the clay lunettes differ topographically from the normal littoral foreshore quartz dunes (Fig. 4B). The latter characteristically have steeper lee slopes reflecting the development of steep down-wind sandslip faces.

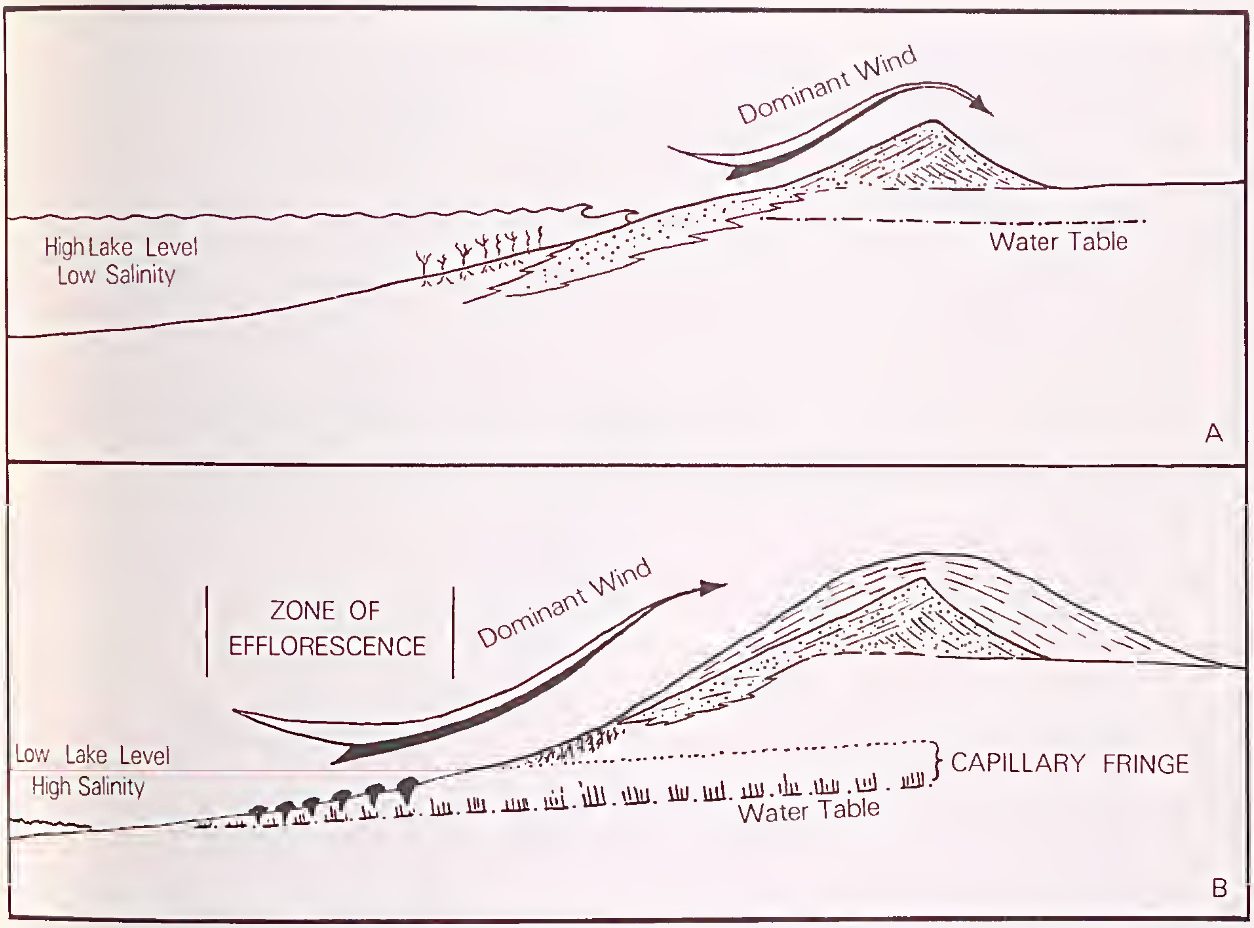

Fig. 4—Cross-sectional diagrams showing the manner of formation of quartz lunettes compared to typical clay-rich lunettes.
A, lacustral conditions; low salinity, deep water environments produce quartz beaches from which transverse quartz dunes formed.
B, relatively arid conditions: surface water deficit results in seasonal exposure of salt flats permitting efflorescence of salts from underlying watertable. Strong winds transport pelletal clays and associated salts to lake margin forming saline clay dune (from Bowler 1980).

This is reflected in cross-bedding as in the L. Kanyapella dune or in the quartz sand component of the Walls of China (L. Mungo) and L. Albacutya lunettes. The clay lunettes on the other hand often possess steep inner, windward slopes and low gentle leeward gradients (see Fig. 3; Hills 1940). This is in part a reflection of their internal structure in which low angle bedding is characteristic. Beds consist of alternate quartz-rich or clay-rich sands from 2 to 30 cm thick at L. Garnpung and L. Albacutya, or as minute laminae a few millimetres thick as on the Walls of China. The angles of deposition are almost always less than 15° on both inner and outer slopes; steep avalanche bedding and cross-set laminae are rarely developed. Thus the clay dunes in their topography and especially in their structure are distinct from quartz dunes where saltation movement results in sand-piling and development of slip faces.

ORIENTATION

The orientation of lunettes on the eastern side of lakes in southern Australia is consistent with the trend of associated east-west linear dunes reflecting the controlling influence of the westerly winds (Hills 1939, Smith, Herriot & Johnston 1943).

A chord joining the 'horns' of the lunette may be used as a measure of orientation. Another measure is a line which passes through the centre of the lake and bisects the lunette into equal parts. This axis of symmetry will intersect the chord approximately at right angles in symmetrical lakes but not in assymmetrical

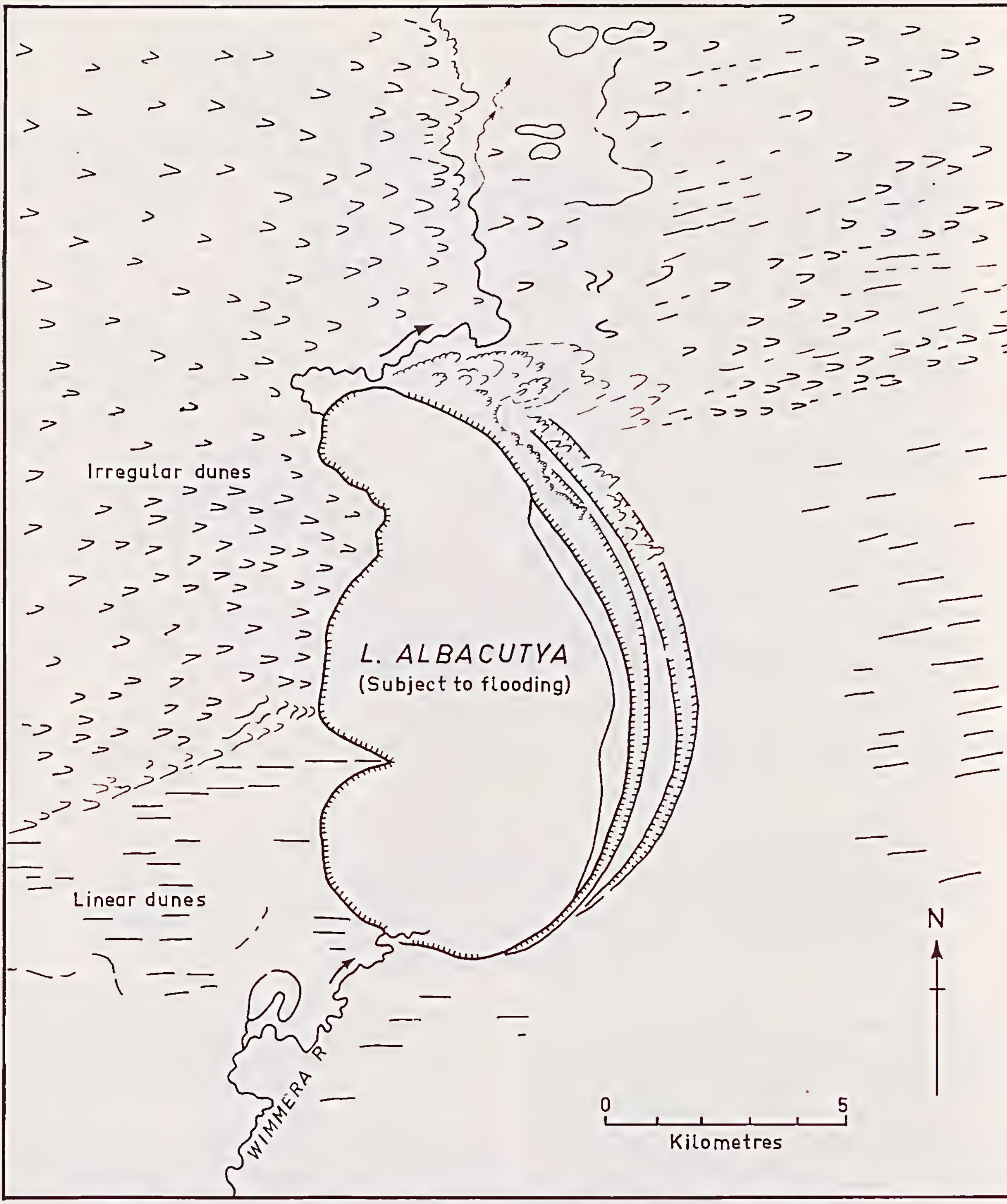

Fig. 5—Map showing the geomorphic setting and features of Lake Albacutya. Note multiple lunette ridges with irregular sub-parabolic lobes of quartz-rich dunes extending downwind from northern margin.

basins. The axis of symmetry which also intersects the lunette at its highest point reflects the direction of the controlling wind regime.

When the orientation of the quartz-rich and cla rich facies are independently measured, several impor ant features emerge. In the quartz-rich lunettes the ax

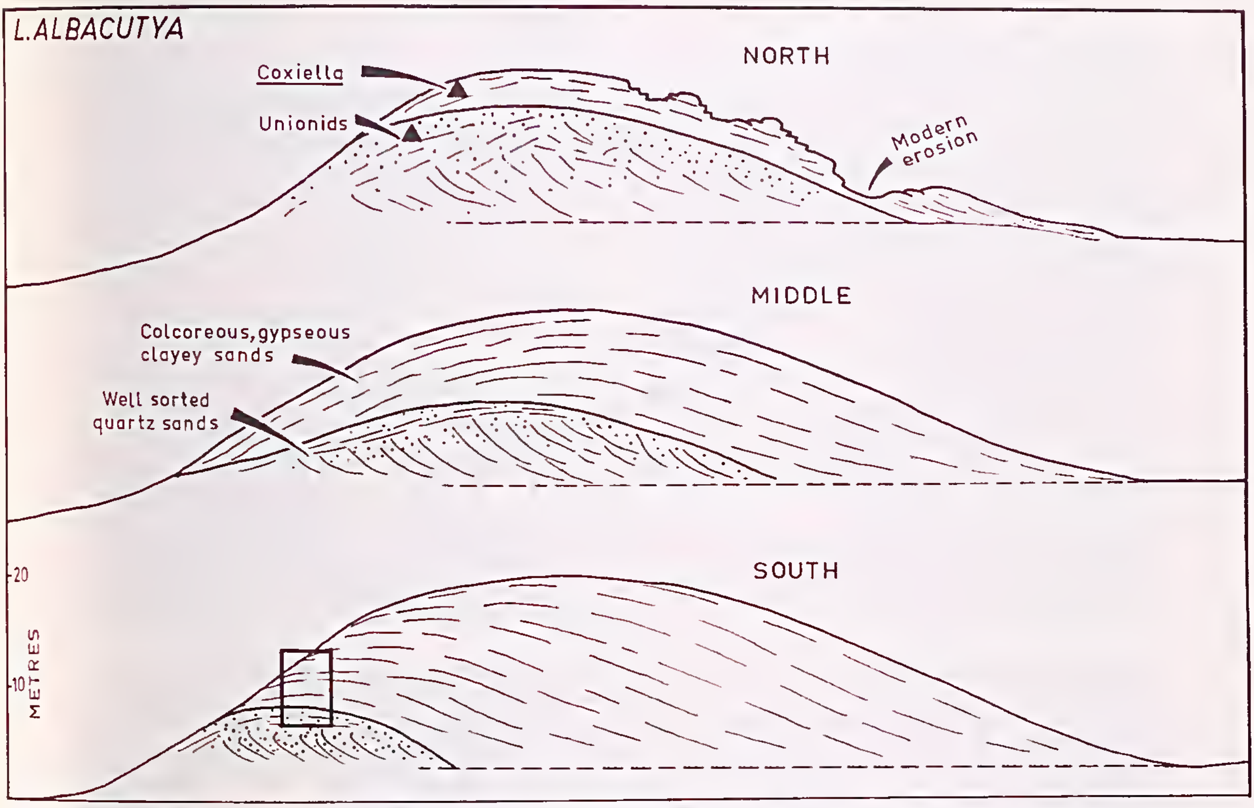

Fig. 6—Stratigraphic sections through inner lunette, L. Albacutya. In the three sections from north to south, the clay blanket thickens reflecting the asymmetric deposition of the quartz and clay members, typical of lunettes of the compound type.

of symmetry usually have a northeasterly orientation parallel to the trends of small parabolic blowouts which sometimes develop on the lunette's outer margin. In the clay-rich dunes the axes of symmetry are usually east-west throughout the Murray Basin.

In the sand lunettes of L. Kanyapella and Little Kanyapella at Echuca, the axis of symmetry has a bearing of 63° compared to approximately 90° for the clay lunettes near Kerang (Fig. 3). Furthermore where linear or Mallee dunes are associated with clay dunes as near Swan Hill, the lunette axes are parallel to the linear trends.

The variation in orientation between the lakeshore quartz and clay components may be found within the sequence on a single lake. On L. Albacutya (Figs 5, 6) the upper blanket cover of clay-rich sediment asymmetrically overlies an earlier quartz-sand component in the inner lunette. On the northern end, the high dune consists of quartz sand. Further south the clay blanket thickens until near the southern end almost the entire dune is composed of the clay component. Thus the quartz sand component has its most prominent development in the northeastern quadrant as at Kanyapella while the later clay-rich blanket has a preferred southeasterly orientation.

This divergence in the disposition of quartz and clay dunes is probably the result of several factors: 1, the orientation of lakeshore beaches which provided the sand source; 2, the direction of the main dune-building winds which do not necessarily coincide with the most effective beach-building winds, and 3, the control of clay dune growth by winds of a particular season.

Discussion of these factors is deferred until the clay-dune building processes have been clarified.

TERMINOLOGY

In choosing the term *lunette*, Hills was drawing attention to two aspects that differentiate these distinctive features from other types of dunes. Firstly, their clay-loam composition placed them in a special category. Secondly, their plan outline with 'horns' facing into rather than away from the prevailing winds imparted a distinctive shape. Finally, their cross-sectional profiles, commonly asymmetric with the steepest face on the windward rather than lee side, stands in marked contrast to barchan type dunes formed by mobile quartz sand with avalanche bedding on the steep lee-sides. These distinguishing elements of composition and form were implicit in the definition of the new landform.

For later workers identifying and using these features several problems arose. In the first stages of mapping, especially at the photogrammetric stages, it is the distinctive morphology which is observed and interpreted. Detailed field examination is necessary to deter-

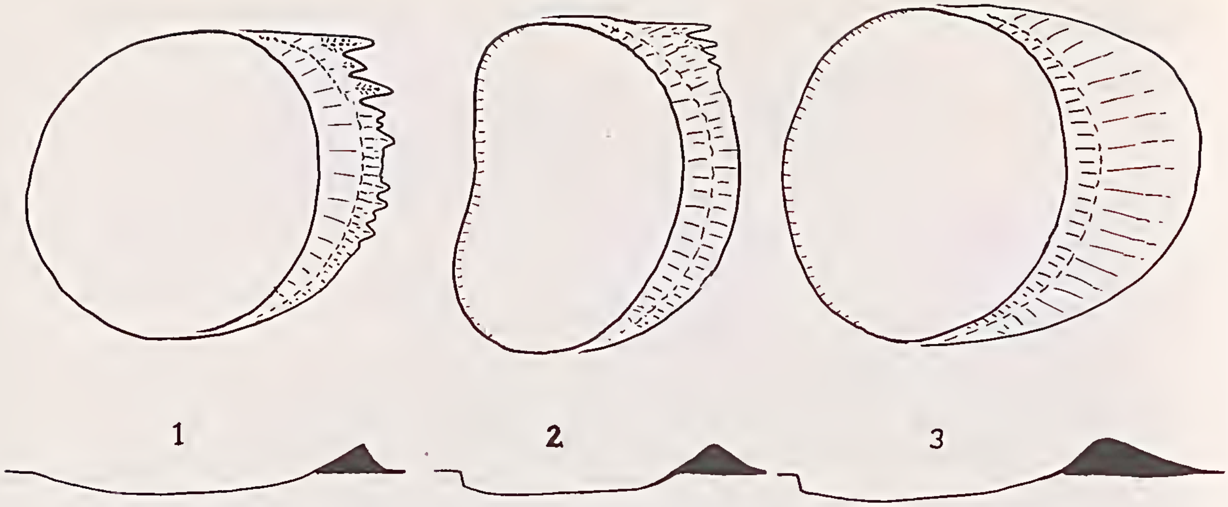

Fig. 7—Plan and section expression of typical basin-lunette associations.
1, quartz foredune, asymmetric with steep leeward slope, often with elongate, sub-linear forms migrating downwind from lee margin. Characteristically no groundwater controlled cliff on upwind margin. Typical example, L. Kanyapella—Fig. 3B.
2, Impure quartz lunette, may be of compound type (quartz core with clay-rich blanket cover). Nearly symmetrical in section, upwind cliff provides evidence of slope retreat controlled by groundwater outcrop zone either past or present. Example, L. Albacutya—Fig. 5.
3, typical clay or gypseous clay lunette, asymmetric profile with steep windward slope. Example, L. Wandella—Fig. 3A.

Note that role of salts in evolution of basins and associated dunes becomes more effective from type 1, low salinity, beach controlled dune to saline groundwater control of processes and products in type 3.

mine if a crescentic lake-shore dune is composed of clay, sand, gypsum or a mixture of all three. In some lakes, the cross-sectional asymmetry is clear enough to provide immediate indications of high clay content. It is equally true that some quartz dunes are identifiable by reason of irregular blowouts on the downwind margin (cf Figs 3A, B, 7).

In some cases, it is not possible from aerial photography or topo-profiles to estimate composition; all are lunate in plan and therefore constitute a group of lakeshore transverse aeolian forms. Moreover, in some areas both quartz- and clay-rich dunes occur in proximity to or in combination with each other.

In those instances where the lunettes possess all the characteristics described by Hills, such as at Kerang and Lake Cooper which are classical representatives of the original definition, the term always implies a clay-rich composition. But composition may range through a wide range of mineral associations from clay through gypseous to quartz-rich dunes with a variety of mixed components. Thus the sand-sized gypsum-rich lakeshore irregular dunes on the margin of Lake Frome with analogues in Lake Tyrrell are very different from the small irregular forms at Kerang. Both have formed under late glacial conditions about the same time and by similar processes but the resultant forms are very different. The variation results not only from different compositon but also from a difference in scale. Thus the huge clay-rich dune complex of Chibnalwood (Willandra Lakes) with irregular gullied form are morphologically more complex than those found on smaller lake basins (Dare-Edwards 1982). Bearing these factors in mind, it is both logical and consistent to apply an adjective to specify composition. Thus *lunette* denotes a transverse crescentic lakeshore dune the composition of which is specified by the appropriate term, clay or loam lunette, quartz sand lunette, gypsum lunette and so on.

An additional complication arises when we consider internal structure. Many lunate dunes when seen in cross-section, are composed of two units or texturally differentiated members. In gully sections at Albacutya (Fig. 6) quartz sands are often overlain by clay-rich sediments. Thus not only have there been different phases of lunette formation, but the sedimentary variations suggest different processes of dune construction on the same lake at different times. When these multiple units are involved, we may specify them as being *compound* types (cf Fig. 4B).

CLAY DUNES

Textures and Structures

The high clay content affects all aspects of clay lunettes including their topography, internal structure and origin; it presents a number of important questions: A, what physico-chemical conditions control their origins? B, are such environments represented in Australia today?

Fig. 8 – Walls of China, Lake Mungo.
A, view north along southern margin of eroding lunette showing residual with planar bedding dipping at low angle towards lake floor on left.
B, Close up of central area of 8A. Alternate laminae of quartz-rich and clay-rich sediment have been deposited in a conformable sequence helping to produce the layer-by-layer succession characteristic of lunette growth (cf. Fig. 10, active clay dune in Texas).

The relevance of pelletal clay aggregates derived from drying mud on exposed lake floors first considered by Hills (1940, p. 4) was rejected because insufficient information was available to establish detailed similarity between the Texas clay dunes of Coffey (1909) and the Australian examples. The idea was revived later

(Stephens & Crocker 1946, Bettenay 1962) on the basis of Huffman and Price's (1949) description of clay pellets moving across tidal flats at Corpus Christi, Texas.

The first accurate Australian observation of clay pelletal aggregates with a description of their size and structure was made in an unpublished report by J. R. Sleeman of CSIRO (1973). He examined two samples in thin section, one from L. Cooper, the other from an undesignated lake near Kerang. Subsequently I have observed them in sections from all clay lunettes studied.

The clays occur in varying percentages of subrounded to elongated aggregates associated with quartz sands. Sorting and the size range of grains varies from bed to bed but within any particular layer, the size of clay pellets and associated quartz sands are similar, indicating that both have been subjected to identical sorting and transporting processes. The proportion of clay pellets to quartz grains varies considerably from dune to dune, and large variations may occur within a single dune. Thus in the Chibnalwood lunette the ratio of pelletal aggregate to quartz sand is approximately 4:1 (Dare-Edwards 1982) whereas through most of the Walls of China it is less than 1:1. But within a single dune such as the Walls of China or the L. Albacutya lunette, large variations in the clay pellet to sand ratio may extend from approximately 5:1 to 0.2:1. These changes in turn are reflected in textural analyses and result in bedding differentiation. Clay aggregates sometimes enclose silt and fine sand-sized quartz and carbonate crystals, although the percentage of silt (62 to 4 microns) is invariably small.

Thin-sections demonstrate the effective sorting of the primary sediment, a feature which is not apparent in the deflocculated samples. These instead, show strong bimodal peaks, one in the sand range near 0.2 mm, the other in the clay range.

The textural variation within the dunes also controls the type of sedimentary structures developed. Thus bedding is often diffuse being defined by alternate bands varying slightly in clay content, while finely laminated low angle bedding is often preserved below the solum, especially in sandier zones. For example, the fine laminae characteristic of the major part of the Zanci unit on the Walls of China (Fig. 8) when examined in section consists of well sorted sands and clayey sands with each lamina having a modal diameter reflecting a sedimentary population distinct from that of its neighbour.

The presence of texturally different layers, each with its own uniform population characteristics, demonstrates a mode of origin for the clay dunes different from that of quartz dunes. The growth of sand dunes by saltation transport up gentle windward slopes and the development of steep leeward sand-slip faces is well known. The downwind migration of the dune or lateral shifting of the crest results in successive erosion and deposition alternately truncating bedding and burying earlier deposits, a process which results in the cross-bedding normally associated with aeolian sediments. In the clay dunes, however, both the steep sand-slip faces and truncation of bedding planes are normally absent (Fig. 8). Once deposited, each gently dipping layer must have remained stable during later depositional episodes. When seen in cross-section, bedding conforms to the topography of the dune reflecting successive stages in dune growth, with each bed superimposed uniformly over the last. Mobile dune forms were apparently not developed.

In the sequential generation of a clay lunette of the Wandella type the maintenance of constant low angle bedding combined with upward growth is associated with downwind migration of the dune crest (Fig. 9). Thus, where successive aeolian stratigraphic units are superimposed over each other as at Lake Mungo, the older units often outcrop or occur at shallow depth on the lakeward margin (Fig. 8).

DISTRIBUTION OF SALTS

Clay lunettes usually contain carbonate except those where deep pedogenesis has affected its removal from one level, concentrating it lower in the profile (Fig. 6). Gypsum is the only other soluble salt frequently observed in crystalline form; its occurrence is variable through the region. It is more common in clay dunes with a high clay content such as the Albacutya lunette than in the more sandy textured dunes where it may be absent as at Kanyapella.

Chlorides which originally would have accompanied clays derived from the saline lakes are not retained in crystalline form, although soils down-wind from lunettes often have high chloride contents (Macumber 1968, 1970) while the lunette clays retain high chloride exchange capacities (Dare-Edwards 1979). The highly soluble chloride, has been mainly leached from the dunes soon after deposition.

MOLLUSCA

The lacustrine faunas, especially the mollusca, provide additional evidence of sedimentary facies and depositional environments. They often occur in the lunettes where they were transported by wind action or, in the case of edible mussels, by man.

As early as 1836 the distinction between fresh-water and salt-water faunas was recognised. On the shores of an undesignated dry lake near Kerang, Mitchell (1839, p. 147) recognised overgrown aboriginal middens consisting of mussel shells collected from the lake. Later at Mitre Lake near the Grampians, he identified shells, which were almost certainly the inland water gasteropod *Coxiella*.

In the mollusca from the lunettes of the Willandra Lakes (Table 1) two principal assemblages are present each of which represent different salinity conditions. The unionids represented by the large *Velesunio ambiguus* represent the low salinity, fresh to brackish water environment, while *Coxiella* represents the high salinity facies.

Table 1

Faunal List from Lunettes on L. Mungo, Outer Arumpo and L. Chibnalwood

**Velesunio ambiguus*	Large fresh to brackish water unionid
**Lympaea tomentosa*	Sinistral coiled gasteropod
**Bulinus (Isadorella) newcombi*	Planorbid dextral coiled gasteropod
**Corbiculina* or *Sphaerium* sp.	Small lamellibranch
**Pupoides (Themapupa) adelaidae* or *beltiana*	Small land snails
Coxiella	Small salt tolerant gasteropod

* Identifications by Dr Brian Smith, Museum of Victoria.

Within the same region, the occurrence of unionids and *Coxiella* are mutually exclusive. In the Willandra system the sediments representing the Outer Arumpo high water level phase contain unionids associated with ostracods. During the final phase of Zanci deposition equivalent to the building of the Chibnalwood lunette an important faunal transition occurred; unionids disappeared and were replaced by *Coxiella* (Bowler 1971). An identical situation occurs in L. Albacutya where unionids occur in quartz sand in the core of the inner lunette corresponding to the low salinity, beach-derived facies; this is overlain by the gypseous clay blanket with *Coxiella* (Fig. 6). The faunal assemblage again corresponds to the change in the sedimentary facies.

MODERN ANALOGUES

As stated earlier, the clay lunettes of southeastern Australia represent fossil landforms, the legacy of earlier hydrologic events. Whilst small local occurrences of active deflation are known (Currey 1964, Macumber 1970) until recently, detailed observations of processes operating on the larger scale analogous to clay dune building were confined to examples outside Australia, notably Texas and North Africa. We now have from within eastern Australian inland basins, several documented examples of clay deflation sites, one from Lake Tyrrell, the other from the floor of Lake Eyre. Before considering these we should consider the Australian fossil forms in the context of examples described from other countries.

The first recorded and best documented of the modern examples are those of the Gulf of Mexico described initially by Coffey (1909) and subsequently studied in detail by Price (1948, 1963). Comparing morphology, textures and structures of Australian fossil forms and modern Texan examples (Figs 8, 10) confirms beyond doubt that the processes of formation are essentially the same in both regions (Bowler 1973).

The process described by Price and his co-workers has been outlined as follows (Price 1963, p. 767): 1, bare saline flats in dry regions crust over after prolonged insolation and wind action, the crust breaking down into aggregates of aeolian fineness, with sand-sized aggregates prominent in the debris. The aeolian aggregates are blown to leeward and form accumulations much like those formed where individual grains are sand size (Fig. 10). 2, the drying crust has been described as breaking down by three different methods: a, through the efflorescent growth of fine-grained, closely-spaced crystals of evaporite salts penetrating the upper layer of the crust; b, by the development in the upper layer of the crust of a microrelief pattern of domal blisters which break down with further drying; c, by the curling up of the thin

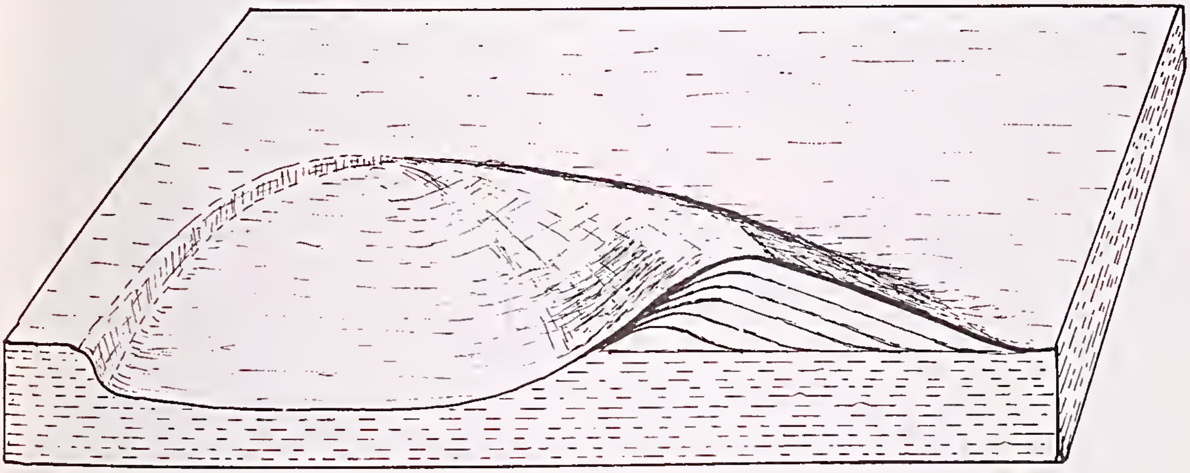

Fig. 9 – Block diagram to illustrate morphologic features and growth stages of a typical clay lunette as evidenced from internal structures. Note that with preservation of low angle bedding, upward growth involves crestal migration away from lake source. Fossil cliff, characteristically present on upwind basin margin provides evidence of former (or present) groundwater outcrop zone producing active recession at toe of slope.

Fig. 10—Laguna Madre, Texas, 1969. View south towards lagoonal salt flat showing clay dunes accreting in the lee side of paling fence. Note planar laminae (cf. Fig. 8B) and polygonal crust developed on surface effectively preventing pellet migration between seasonal deflation episodes.

fragile surface layer of sun-cracked polygon chips which are then broken down mechanically by being swept to leeward along the surface of the crust. Where a layer of algae has formed on the crust, it retards deflation and its desiccation produces papery fibres which move with the other crustal debris. As the disintegrating crustal debris is blown to leeward, the wind sorts out the sand-sized aggregates and accumulates them on the crust or on rising ground of the border where they may be arrested by vegetation, chiefly of a grassy nature.

These features find equivalent expression in the ancient dunes of southeastern Australia. In thin-section both modern and ancient forms consist of sand-sized pelletal aggregates confirming that the Australian aeolian clays were derived from salinised lake floor in exactly the same way as those forming today near Corpus Christi, Texas.

Secondly, in a small 'satellite' pan on the east side of Tyrrell which we have named 'Pup Lagoon' (Fig. 11), clay pellet deflation occurs seasonally under today's climate. This is controlled by a groundwater regime, slightly different from that of the main basin from which the pan is separated by an aeolian barrier. The floor of the deflation pan is located a mere 70 cm above the main basin; it is subject to seasonal flooding, followed by drying, fall in watertable, efflorescence of salts in preparation for seasonally strong winds to transport the pellets to the eastern margin (Figs 12, 13).

Once the pellets are transported to the leeward margin they are trapped by vegetation and effectively stabilised by the hygroscopic action of enclosed salts, particularly halite, when temperatures fall and humidity nears dew point.

The deflationary process results here from the adventitious isolation from the main basin and especially the 70 cm difference in mud-flat surfaces. This small but significant difference and its influence on the deflation processes highlight the hydrological sensitivity of clay dune building.

DEFLATION FROM LAKE TYRRELL FLOOR, JANUARY, 1983

An instructive example of modern clay deflation occurred at Lake Tyrrell on January 26th, 1983. That day coincided with the passage of a cool front through southeastern Australia following a period of high summer temperature often exceeding 38°C. Strong southwesterly winds associated with the frontal system were raising great clouds of brownish dust from the dry, eroding wheatfields. Such dust originated mainly as a result of cultivation and grazing. On the other hand, from the lake floor, an area spared from man's direct interference, grey billowing plumes swept eastwards with each strong gust of wind, a phenomenon not observed previously here outside the narrow confines of Pup Lagoon. On this occasion the long drought through the preceding year had ensured effective desiccation of the playa surface. Strangely, the floor of Pup Lagoon remained stable although extensive pellet movement was occurring around its marginal samphire zone.

A transect across the playa margin on the east side near Pup Lagoon delineates 5 zones on the basis of topography, vegetation and hydrologic conditions (Fig. 14). A marginal chenopod zone (zone A, Fig. 14) on gypseous grey clays forms the eastern ridge rising about 6-8 m above the playa floor, passing down via a steep slope to a basal zone of succulent samphire (zone B). This frequently possesses a soft surface of pelletal fluffy clays prepared by efflorescence from the watertable lying 1 to 1.5 m below. On this day in 1983 strong winds were raising dust clouds from this zone, removing sediment in suspension and piling sandy pellets into shrub-coppice dunes around the toe of the slope and extending well up onto the chenopod ridge. This removal of sediment from the toe of slope constitutes a most important process in controlling over-steepening and slope retreat with consequent erosion of the underlying lacustrine or, in this case, aeolian sediment.

At the lakeshore edge of the samphire zone, an area usually boggy and impassable to vehicles, the watertable remained near the surface in January producing a soft slushy zone despite the long period of desiccation (zone C). Its permanent saturation ensures the relative stability of this surface as far as deflation is concerned. It was observed to be arresting some pellets in transit across it so that it appears rather as a potential accretion rather than deflation zone.

Fig. 11 – Geomorphic map of L. Tyrrell showing location of Pup Lagoon, site of modern clay dune accretion. Note multiple ridges on east representing ancient development of lunettes during periods of Pleistocene hydrologic change.

Fig. 12—Clay deflation site at Pup Lagoon on margin of Lake Tyrrell.
A, summer conditions showing active deflation from clay flat in middle distance under the influence of southwesterly winds, Jan. 27, 1978. B, winter conditions with footprints leading across gluey mudflat to a small excavation site dug during previous summer. C, wall of excavation when freshly dug. Desiccation cracks pass down through greyish brown clays becoming black and sulphide-rich near the watertable at 50 cm in floor of pit. Desiccation cracks provide pathways for capillary evaporative loss and facilitate efflorescence and pelletisation at the surface. D, floor of Pup Lagoon during following summer showing early stage in the preparation for deflation. Desiccation polygons are outlined by dark puffy zones of efflorescence and clay pellet generation. Winds later in the season reproduce conditions as in 12A.

The main site of deflation on the playa floor was restricted to a zone marginal to the very outer edge of the salt crust (zone D). Where the crust was very thin (1-2 mm only) slight buckling along tee-pee pressure

Fig. 13—Eastern margin of Pup Lagoon showing a rippled zone of clay pellets advancing eastwards to be trapped in dark samphire vegetation resulting in active clay dune growth to 1.5 m above clay flat. Skyline in background represents ancient lunette ridge built during the 36 000-16 000 BP dune building episode.

ridges was permitting strong winds to flip over and break up the salt flakes thus exposing the underlying clays to more intense drying (Fig. 15). A curious micro-hydrologic phenomenon existed here. Below undisturbed salt flakes, underlying clays were soft, slippery and water-saturated. By comparison, in those pelletal fluffy zones just a few centimetres to the east from which the crust had been removed by wind, the aerated zone to 5 cm and below seemed thoroughly dry. Apparently the salt layer, although very thin, is an effective inhibitor of evaporation loss. As soon as the crust is disturbed a completely new set of local conditions is initiated. Evaporative loss from the watertable (estimated to have been about 50 cm below) set up the interstitial salt efflorescence within the drying clays.

At Tyrrell on Jan. 26th, these processes produced a thin 1-2 cm layer of needle halite with crystal elongation perpendicular to the surface indicating upward growth. It was this phenomenon that was responsible for pushing up and breaking the surface clays. Driven by gusts of strong winds in excess of 30 km/hr, clouds of grey clay billowed off the lake surface while rippled ribbons of traction pellets streamed across the playa floor to be trapped in the marginal samphire producing an active clay dune ridge (Figs 13, 16).

These processes observed at Tyrrell and known to occur in almost identical fashion at Lake Eyre provide modern analogues of the climatic, hydrologic and micro-processes necessary to construct the larger, thick, lunette ridges of Late Pleistocene age. In so doing they provide excellent examples in helping to reconstruct those conditions that prevailed across southern Australia during the windy summers of some 16 000 to 36 000 years ago.

In both the Texan and Tyrrell examples (Fig. 16), the advent of rain or onset of high humidity and low temperatures results in the formation of a surface crust 2-4 mm thick cemented mainly by halite, and sealing the active layer (Fig. 10). Within this crustal film clay pellets coalesce forming a stable protective envelope around free-flowing aggregates. Thus after the short seasonal dune growth the thin pelletal layer is permanently stabilised during the following humid season. In this way maximum progradation occurs in the inner dune slope. Pellets rarely form thick mobile accumulations; the steep sandslip faces of such accumulations have been recorded only during long droughts and periods of exceptional aeolian activity (Price 1963, p. 773).

In a recent field exercise at Lake Eyre, Mr. John Magee of the Department of Biogeography and Geomorphology established the presence of a broad zone of soft fluffy pelletal clays which under the influence of strong winds, is subject to active deflation (Fig. 17). This zone, apparently operating under the same processes described from Texas and Pup Lagoon, provides an example of extensive clay deflation from an inland salina, the actual extent and regional importance of which has yet to be identified.

Salts

The role of salts in the clay pellet formation has been discussed by Price and Kornicker, (1961, p. 247) who recognise 'two phases of deflation in the flats'. In the first 'mudcrack polygon laminae break down when separated from the flat by wind as the particles are transported to the shore'. In the second phase, salt efflorescence breaks down clay into sand-sized pellets 'of quartzitic sand and silt in an envelope or with a matrix of lutitic sediment', a description which almost precisely corresponds to the fabric preserved within the Australian lunette sediments described above. Analyses of the mobile efflorescent layer from Tyrrell sites and Lake Eyre are set out in Table 2.

At L. Eyre and the floor of L. Tyrrell salts in the mobile pelletal layer are dominated by halite and gypsum while on Pup Lagoon the more soluble thenardite plays an important role. Previously gypsum crystallisation was thought to be the active component in clay pelletisation since, in the clay lunettes, it is almost always present. However, the gypsum being the 'millet seed' or discoidal variety is now known to have crystallised interstitially from groundwater during an earlier phase of the drying cycle before the efflorescence of the more soluble chloride and sodium sulphate. Indeed it is these more soluble components and especially halite which provide the active agents that prepare the clay surface for deflation as the analyses in Table 2 confirm.

Other factors

Macumber (1970) questioned the need for surface water to be present in the initial stages of lunette formation. His evidence is drawn from topographically low

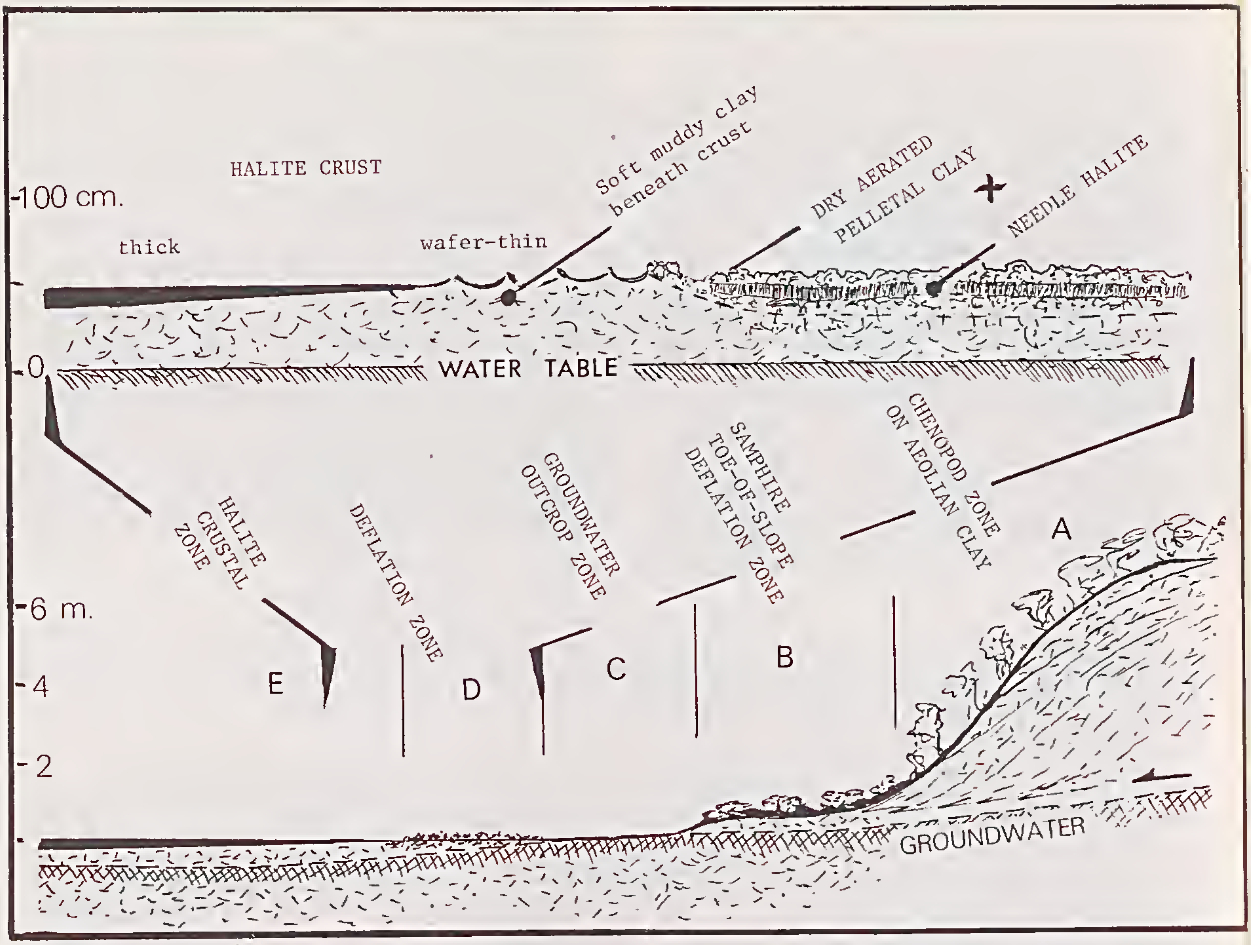

Fig. 14—West to east section across the eastern margin of L. Tyrrell showing relationship between topography, groundwater, halite crust and two active deflation zones: zone B at toe of main slope and zone D at edge of halite crust of playa floor. Width of zone D when active deflation observed on 26 Jan. 1983, ranged from less than 1 m to more than several hundred metres. Note development of vertically elongate needle halite, the active ingredient responsible for producing clay pelletisation in areas from which the salt crust was absent or broken up by wind.

and almost indiscernible ridges in the Kerang area which have developed by erosion of adjacent salt-affected areas. Macumber envisages vegetation destruction and breakdown in soil structure due to salinisation which may occur in low-lying areas after local or regionally controlled changes in watertables. Soil thus affected becomes liable to wind erosion which transports clay aggregates into the vegetated margin of the salt-affected area. This realistic explanation of such features must be taken into account in explaining the initiation of deflation basins.

In the Texas environment, the main aeolian transport of clays occurs between the months of March and November (Huffman & Price 1949, p. 120) in warm to hot seasons when strong insolation corresponds to steady onshore winds (Price & Kornicker 1961, p. 246). The summer months June, July, and August are characterised by strong winds from the southeast quadrant. In June with mean maximum air temperatures of 28°C more than 50% of all winds blow from the southeast and more than 30% are greater than force 5. The coincidence of a strong, almost unidirectional wind regime and high summer insolation provides the conditions best suited for the drying of the flats, and formation of pelletal aggregates and transport into the northwestern lakeshore dunes. In southeastern Australia the surface is prepared by high evaporation rates following the winter wet season with the actual deflation process being restricted to periods of high wind velocity associated with the passage of frontal systems. Thus in the southeast at Lake Tyrrell, these are associated with both the northwesterlies that precede frontal systems and strong southwesterlies that often follow the passage of the front especially in summer. The process may continue until the onset of the next humid season usually in late autumn or winter. These conditions in the winter rainfall zone would almost certainly have prevailed during the Pleistocene production of major clay lunettes.

TABLE 2

CHEMICAL AND MINERALOGIC COMPOSITION OF MOBILE EFFLORESCENT ZONE CLAYS AND SALTS FROM LAKE EYRE, PUP LAGOON AT LAKE TYRRELL AND TYRRELL FLOOR.

Chemical data reported as weight per cent. Analyses by Jim Caldwell, Dept. Biogeography & Geomorphology, ANU.

MOBILE EFFLORESCENT LAYER			
WET CHEMISTRY (needle halite layer, Fig. 10)	L. Eyre	Pup Lagoon	L. Tyrrell Floor
Total sulphate SO_4	6.25	10.5	1.57
Water-soluble SO_4	0.91	5.6	1.32
Insoluble sulphate (gypsum, by difference)	5.34	4.9	0.25
Total chloride Cl	15.26	0.24	29.14
Water-soluble CO_3	0.002	tr	NIL
Water-soluble HCO_3	0.039	0.024	NIL
Total carbonate CO_3	0.76	0.40	NIL
Organic C	0.26	N.A.	N.A.
1:5 pH	8.41	8.99	6.56
Na:K	190	35	
CALCULATED SALTS			
$CaSO_4.2H_2O$	9.57	8.80	0.44
Na_2SO_4	1.35	8.3	NIL
NaCl	25.16	0.40	47.0
Ca(M)CO_3	1.20	0.29	NIL
$NaHCO_3$	0.05	0.22	NIL
$MgSO_4$	NIL	NIL	1.6
X-RAY DIFFRACTION			
	Gypsum	Gypsum	Halite
	Thenardite	Quartz	Quartz
	Halite	Thenardite	
	Quartz	Disordered kaolin	Gypsum
	Kaolin	Illite	Illite
	Illite	Palygorskite (?)	Kaolinite
	Palygorskite	Hi-Mg calcite	
	Calcite	Halite	

Processes similar to those described here have been recorded by Boulaine (1956) in Algeria and by Coque (1962) in nearby Tunisia. In both cases they are related to inland basins controlled by saline groundwater regimes. In coastal west Africa, Tricart (1954) recorded the formation of small dunes (*bourrelets*) in estuarine environments of subtropical Mauritania and Senegal while more recently, Rhodes (1982) has described the seasonal mobilisation of pelletal clays on saline mud flats on the coastal fringe of the Gulf of Carpentaria. Thus the formation of clay dunes is not restricted to saline groundwaters of inland basins but may be active in many coastal regions.

An interesting clay dune occurrence has been recorded in the salinas of Patagonia by R. W. Galloway (*pers. comm.*) where seasonal aridity associated with saline groundwater produces pelletal aggregates which, in turn, are blown into lee-side dunes by very high velocity westerly winds. The significance of this occurrence lies in the temperature regime of dune building; whereas all other examples recorded here lie in tropical or sub-tropical latitudes those in Patagonia are formed in cold high latitude arid conditions.

SOUTHERN AUSTRALIAN CLAY LUNETTES: SUMMARY OF FORMATION

CHRONOLOGY

Substantial evidence indicates that the last period of major clay dune construction occurred in southeastern Australia about 17 000 B.P. (Bowler 1976, Sprigg 1979). Radiocarbon dates for this event represented by the Zanci Unit in the Willandra Lakes sequence, cluster between 17 500 and 16 000 B.P. in that region. Additional C 14 ages for lunettes at Albacutya, Lake Frome, Lake Corangamite, Lake Victoria (Gill 1971, 1973) and even in southwest of Western Australia point towards situations of regional extent permitting synchronous and large scale development of clay and gypseous clay dunes at this time. Although this corresponds to the last and most active period of clay dune building, earlier late glacial episodes are known. At Lake Mungo, the first clay dunes may have started as early as 30 000 B.P. but with intermittent deep-water conditions persisting until

Fig. 15 — L. Tyrrell floor, 26 Jan. 1983. Buckling zone with teepee structures in thin salt crust is broken by strong winds permitting drying and pelletisation of underlying clays. Note pellets drifting over crustal surface. Knife blades scale is 15 cm long.

Fig. 16—A, Laguna Madre, Texas, Sept. 1969. Shrub coppice clay mound accumulation on northern side of the tidal salt flat visible in background. Note crustal skin on mound and mud curls in depression developed after stabilisation by rain.
B, Lake Tyrrell, Jan. 1983. Rippled mounds of clay pellets accumulate in samphire vegetation under influence of southwesterly winds.

after 25 000 B.P. The controlling conditions may be determined by comparison with modern processes enabling us to reconstruct the hydrologic parameters that existed throughout the area during clay dune construction.

WATER AND SALTS

In the various theories of Australian lunette formation controversy centres on the presence or absence of water in the adjacent lake. The occurrence of modern clay dunes requires a particular combination of salinity and hydrologic regime, within which flooding plays an important part. In Texas, the clay flats remain bare and favourable to clay dune formation due to the periodic flooding by saline waters which prevent vegetation colonisation; on drying, efflorescence of salts assists in producing the clay aggregates. Flooding by sea water is similarly responsible for dune formation in the Casamance example (Vieillefon 1967) and on the West African Senegal delta region (Tricart 1954); in the Algerian example the seasonal inundation and the concentration of salt is ensured by high groundwater levels and by strong seasonality. In every example the presence of water is necessary to act as a vehicle to concentrate and distribute the salts.

The presence of salts, especially concentration of chloride, is necessary for two reasons. Firstly high salinities inhibit vegetation colonisation which would otherwise trap aeolian sediment on the dry lake floor. Secondly, the efflorescence of salts in the exposed clays provides one of the most important ways of producing sand-sized pelletal clay aggregates. This is the process which operates today on Lake Eyre, Lake Tyrrell, Pup Lagoon and on the margin of salinised depressions in the Kerang and Swan Hill districts during periods of summer drying and reduction in water level.

Tricart's comments (1954, p. 130), summarising the importance of saline waters in the deflationary evolution of sebkhas, apply equally well to their deflationary products in Africa as to clay lunettes in Australia. He emphasised the need for a continuous and relatively large supply of salts. In areas with high evaporation this can be ensured by a large seasonal inflow of fresh to brackish water from which the salt is concentrated during the dry season. Conversely, areas initially high in sulphates, carbonates, and chlorides are particularly favourable for the formation of solanchaks, which in turn are liable to erosion, dune formation and basin development.

During aeolian deposition chlorides are rapidly leached from the dune into the basin while carbonate and sulphate are retained in the aeolian sediment. The lunette-forming process and its associated hydrologic regime therefore represent a salt-separation environment as described by Boulaine (1954, p. 115). This helps preserve high chloride concentrations within the basin while calcite, dolomite and gypsum are preferentially removed.

As implied by Macumber (1970), the level and quality of groundwater relative to the basin floor are critical for clay deflation. Today the seasonal rise and fall of approx. 70 cm below the floor of the mud flat at Pup Lagoon provides the driving mechanism enabling seasonal efflorescence from chloride saturated waters and pellet formation to occur. But as indicated earlier, this is a purely adventitious circumstance controlled by the slight difference in elevation between Pup Lagoon and the main basin floor which remains a groundwater outcrop zone throughout most of the year. Thus today, the conditions for regional and large scale dune building in southern Australia do not exist. This stands in marked contrast to conditions of late Pleistocene when numerous basins in southern Australia were actively producing such dunes. The explanation for these extraordinary conditions is twofold.

Firstly, the deflation and clay dune building conditions were preceded by a phase of regionally high watertables, the Mungo Lacustral Phase in southeastern Australia. In this period numerous basins which are now dry, were brim full of fresh water as their unionid faunas attest. This would certainly have resulted in regional watertables being much higher than today's. But with the change to a negative hydrologic budget that followed, surface waters diminished, lakes became saline and basins, previously fresh, were converted to groundwater discharge points. This reversal of the hydrologic balance corresponding to a major climatic change, produced conditions necessary for clay pellet formation and dune building.

Secondly, to enable the process to proceed in lakes such as Tyrrell or Frome where the watertable is at or near today's surface, the discharge budget must have been such that seasonal evaporation exceeded surface and groundwater discharge. This would produce the necessary drop in watertables to allow capillary rise, efflorescence and seasonal drying, a condition which at Frome and Tyrrell is not widespread today. This circumstance would be favoured by a slightly undulating basin floor in contrast to the billiard-table floors which now characterise these basins. Moreover, it was the change from high to low watertables which maintained the regional supply of salts to basins in which no salt supply is available today e.g., the numerous lakes near Hatfield or the Willandra Lakes unconnected to surface drainage.

ROLE OF WIND

In the earlier part of this essay I drew attention to the different disposition of quartz and clay components when both are present in the same locality. The maximum development of the quartz component occurs in the northeastern quadrant while the axis of symmetry of the clay dune has a more east to southeasterly orientation.

Two processes are involved in the orientation of quartz lunettes. The maximum development and orientation of lake beaches which provided the source of the dune sands is controlled by the complex interaction of winds, waves and littoral sediment transport in the lake. This, in turn, is reflected in the maximum development of the quartz foredune. Evidence from modern lakes in the region suggests that maximum beach development occurs in the northeastern quadrant coinciding with the thickest dune sands as on L. Hindmarsh, L. Albacutya and L. Garnpung. In addition, the aeolian transport of quartz sand, although most active in summer, may have occurred at any time of the year provided the beach sands were dry and winds were of sufficient strength.

In the clay dunes, the annual duration of the dune building phase was restricted to a brief interval late in the dry season. Evaporation curves show that water-levels would be lowest, muds driest and conditions best suited for clay deflation at the end of summer or in early autumn.

Modern sand shifting winds ($F. V_t^3$ where V_t is velocity greater than 9 knots) analysed from continuous anemometer records from Mildura airport produced the following seasonal resultants: summer 209°, autumn 242°, winter 273°, spring 248°. The summer resultant with its strong southerly component bears little resemblance to clay lunette orientation which is closer to the autumn or winter resultants. This is consistent with the formation of clay dunes in southern Australia being restricted to the February-April period. The combination of these factors (the construction of lake beaches, and the growth of quartz and clay dunes under different hydrologic conditions) has contributed to the asymmetrical disposition of the quartz and clay components in the lunettes.

Local Hydrologic versus Regional Climatic Influence

In the examples of modern clay lunette formation discussed earlier, the controlling factors are dominantly local hydrology rather than regional climates. In Texas, flooding by sea water provides the triggering mechanism; in Algeria, saline groundwaters are involved in a particular tectonic setting while in Mauritania and Senegal a combination of fluvial and estuarine factors create the circumstances in which clay dunes form. The dunes are not controlled by climate alone.

The dominant influence of hydrologic factors other than climate is further evident in the distribution of the modern examples. On the Gulf of Mexico, clay dunes extend from the sub-humid zone near Corpus Christi south into the semi-arid regions of Mexico. Similarly in the Mauritanian-Senegal occurrences, precipitation increases rapidly southwards into the humid tropics but the clay dunes continue across the climatic gradient. This is reminiscent of a similar azonal distribution of the ancient Australian examples where lunettes of last glacial age occur from central Australia (Lake Eyre, Lake Frome region) through what are today semi-arid regions of the Murray Basin and the southwest of Western Australia and into the sub-humid and even humid regions of western Victoria and at Lake Omeo, in the southeastern highlands.

Fig. 17—Footprints in soft rippled pelletal clays in active deflation zone at L. Eyre, October 1982. (Photo J. W. Magee)

A striking feature of the Australian examples is that not only did hydrologically suitable conditions for lunette formation develop over a wide range of physiographic and climatic settings but that these critical water balances should have appeared synchronously over such regions. This could only have been controlled by a major change in climate affecting the entire southern region of the continent in which lunettes that formed at that time remain as fossil remnants today.

The nature of the changes which controlled the synchronous development of glacial age lunettes involves a major contrast between the conditions that prevailed during the period of earlier regionally high lake levels and those that accompanied the drying of lakes and construction of dunes. In this respect it was largely the *direction* of change from regionally wet to regionally dry which made lunette building possible. By contrast, if we experienced a trend towards drier climates today, the landscape response would be quite different from that which characterised the expansion of dune building environments some 16 000-30 000 years ago.

In their history, the lake basins and associated dunes across southern Australia reflects a basic principle of geomorphology, viz. *the nature of the landscape response to any climatic or hydrologic change is determined as much by the pre-existing conditions as by the direction and nature of that change.* Thus the clay-rich and gypsum-rich lunettes of southern Australia represent the end products of a particular set of hydrologic parameters which were set up almost simultaneously over large regions in response to a major shift from regionally wet, high watertable conditions to dry windy environments coinciding closely with the maximum of the last global glaciation.

CONCLUSIONS

In Australia, relatively unaffected by glaciation, the imprint of Quaternary global climatic variations has long been poorly understood. The lunettes discussed here and the changes they represent provide a window into events of glacial age; in so doing they demonstrate how this dry continent responded to late Quaternary global climatic rhythms.

As fossil features from the last glaciation, Australian clay lunettes find present day analogues in active clay dunes on coastal Texas, Senegal and the Gulf of Carpentaria while comparable inland playas are today forming clay dunes in Algeria, Patagonia and in certain parts of Australia. The controlling processes require a special combination of salt-affected surfaces subjected to regular flooding, followed by a seasonally dry climate to permit efflorescence and pelletisation of surface clays. Strong winds are then necessary to transport clay pellets and associated minerals, usually gypsum, to the vegetated playa margin.

The hygroscopic nature of associated salts plays an important part in the depositional behaviour of the clay pellet layers. As temperature falls and relative humidity increases to near dew point, salts associated with the last season's layer of pellets, hygroscopically absorb moisture; the layers become a sticky coalescing mass in which individual pellets adhere to each other so that on drying, a surface crust develops sufficient to stabilise and prevent any further movement. Thus next season's layer is deposited conformably over the last, building a layer-by-layer sequence characteristic of those lunettes where internal structures are preserved. By the nature of its conformable low angle bedding, as the dune grows in height, its axis of symmetry moves downwind thus maintaining its internal geometry.

The clay lunettes across southern Australia formed in response to a particular sequence of hydrologic events, the legacy of which is recorded on many lake basins over wide areas. This sequence began with a substantial wet phase, the Mungo Lacustral, in which many basins now dry were filled with fresh water. The widespread presence of surface water, even in regions now dry, identifies this as a period of major groundwater recharge. From evidence in the Willandra Lakes it appears to have lasted from at least 50 000 B.P. to near 36 000 B.P. marking it as a major period in the climatic evolution of Australian landforms. During this episode many quartz lunettes were formed from high water levels on northeastern lakeshore margins. It was this wet phase which set the scene for later dune building.

With a change from a positive to negative hydrologic budget around 36 000 B.P., surface waters contracted, lake levels fell and many basins were converted to groundwater discharge points. This period corresponded to an increase in salinity, deposition of large quantities of gypsum and eventually resulted in that critical balance of seasonal drying and flooding, the conditions necessary for pelletisation and clay lunette building. Although clay-dune growth proceeded episodically from about 36 000 B.P., the maximum and most widespread phase culminated between 18 000 and 16 000 B.P. signalling the expansion of dune building over large areas of the continent.

The changes recorded in lake basins in terms of salinities and hydrologic variations are no less remarkable than those events of comparable ages and controlled by the same climatic rhythms in other continents. Thus the dramatic advance and retreat of ice sheets in Northern Hemisphere continents, North America or Europe, of the expansive deposition of loess blankets over huge areas of central China or western USSR, these all represent different responses to those same global rhythms that controlled the hydrologic changes and culminated in widespread dune building on the basins of southern Australia. Indeed in the wealth of stratigraphic, archaeologic and palaeoenvironmental information they have yielded over the past 15 years, the Australian lunettes continue to provide some of our richest records of Quaternary geological and human history.

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